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Key Points:

- Lower crust at the 16.5°N region of the Mid-Atlantic Ridge has a bimodal composition
- Thermodynamic models show that this distribution is expected in regions where small gabbroic bodies are intruded into mantle peridotites
- Deformation related to detachment faulting commenced under high-temperature conditions (>1000 °C) as recorded by ultramylonites

Supporting Information:

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Emplacement and High-Temperature Evolution of Gabbros of the 16.5°N Oceanic Core Complexes (Mid-Atlantic Ridge): Insights Into the Compositional Variability of the Lower Oceanic Crust

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Abstract This study reports the composition of the oceanic crust from the 16.5°N region of the Mid-Atlantic Ridge, a spreading ridge segment characterized by a complex detachment fault system and three main oceanic core complexes (southern, central, and northern OCCs). Lithologies recovered from the core complexes include both greenschist facies and weathered pillow basalt, diabase, peridotite, and gabbro, while only weathered and fresh pillow basalt was dredged from the rift valley floor. The gabbros are compositionally bimodal, with the magmatic crust in the region formed by scattered intrusions of chemically primitive plutonic rocks (i.e., dunites and troctolites), associated with evolved oxide-bearing gabbros. We use thermodynamic models to infer that this distribution is expected in regions where small gabbroic bodies are intruded into mantle peridotites. The occurrence of ephemeral magma chambers located in the lithospheric mantle enables large proportions of the melt to be erupted after relatively low degrees of fractionation. A large proportion of the dredged gabbros reveal evidence for deformation at high-temperature conditions. In particular, chemical changes in response to deformation and the occurrence of very high-temperature ultramylonites (>1000 °C) suggest that the deformation related to the oceanic detachment commenced at near-solidus conditions. This event was likely associated with the expulsion of interstitial, evolved magmas from the crystal mush, a mechanism that enhanced the formation of disconnected oxide-gabbro seams or layers often associated with crystal-plastic fabrics in the host gabbros. This granulite-grade event was soon followed by hydrothermal alteration revealed by the formation of amphibole-rich veins at high-temperature conditions (~900 °C).

1. Introduction

Detachment faults, first reported as low-angle normal faults at the MARK area of the Mid-Atlantic Ridge (MAR, Dick et al., 1981; Karson & Dick, 1983), are common at slow-spreading ridges. These long-lived faults terminate at the foot of the rift valley wall and produce a smooth surface with corrugations parallel to the rifting direction (Cann et al., 1997). They expose large sections of lower oceanic crust and abyssal mantle, commonly termed *megamullions* or oceanic core complexes (OCCs) (Cann et al., 1997; Tucholke et al., 1998). The detachment faults operate for up to several million years and exhume lower crust and mantle rocks, which are continuously accreted and emplaced into the rift mountains from beneath a volcanic carapace (Dick et al., 2008). Detachment faulting can account for 60–100% of the plate separation in some ridge sections and may dominate a region for several millions of years (Escartin et al., 2008; MacLeod et al., 2009; Smith et al., 2006, 2008; Schroeder et al., 2007; Tucholke et al., 1998). In particular, Escartin et al. (2008) and Smith et al. (2008) estimated that close to 50% of the MAR from 12.5°N to 35°N is characterized by detachment faults, indicating that a substantial portion of the seafloor in the central portion of the MAR may form by such asymmetric spreading. Recently, some investigators have suggested the proportion of seafloor formed by detachment faulting could be even higher, if more fault surfaces are hidden under basaltic rafted blocks (e.g., Reston & Ranero, 2011). Detachment faulting is now known as a major mechanism of crustal accretion at slow-spreading ridges (Parnell-Turner et al., 2018; Smith et al., 2014).

The nucleation and growth of detachment faults is dependent on many factors, including rheological differences between gabbros and serpentinized mantle peridotites, spreading rate, and magma budget

(e.g., Cannat et al., 2006; Escartin et al., 2008; Ildefonse et al., 2007). For instance, numerical modeling suggests that detachment faults form at intermediate levels of magma supply (e.g., Cannat et al., 2006) at slow- and ultraslow-spreading ridges when the ratio of magmatic accretion to tectonic extension (M) lies between 0.3 and 0.5 (Olive et al., 2010; Tucholke et al., 2008). This is consistent with the common occurrence of gabbroic lithologies exposed along the fault surfaces at OCCs (e.g., Blackman et al., 2006, 2011; Cann et al., 1997; Dick et al., 1981, 2000; MacLeod et al., 2009). In addition, it is likely that the mechanics of detachment faulting in amagmatic environments differs from magmatic ones, where the fault roots into a significant crystal mush zone beneath the rift valley and synmagmatic deformation can enhance fault longevity and control fault geometry (Dick et al., 2000; Natland & Dick, 2001).

OCCs offer a unique opportunity to unravel the composition of the lower crust of ridge segments formed at slow-spreading ridges, although these observations are pertinent to the sections exposed through detachment faulting; to what extent these observations apply to the lower oceanic crust at symmetrically spreading segments is uncertain. The large compositional variability of the gabbros at OCCs worldwide suggests that the lower crust in these sections is not that of the classic Penrose model (Conference Participants, 1972). At the 660-km² gabbro massif at Atlantis Bank on the SW Indian Ridge (Ocean Drilling Program Holes 735B, 1105A, and U1473) most of the gabbros recovered by seafloor sampling and drilling (up to 1.5 km) are olivine-gabbros interspersed with highly evolved (oxide-bearing) gabbros, representing crystallization from nothing close to a primary magmatic liquid (Dick et al., 2000; MacLeod et al., 2017). In contrast, the 1.4-km deep Hole U1309D at the Atlantis massif OCC, another large OCC exposed along the MAR, contains a much broader range of lithologies, with large amounts of primitive gabbros such as troctolite, many gabbro in a strict sense (olivine <5 vol %), and subordinate oxide-gabbros (>2% oxide, Blackman, 2006; Blackman & Collins, 2010). Large amounts of troctolites and olivine gabbros also constitute the isolated intrusions in mantle peridotites at the Kane megamullion, a large detachment system south of the Kane Fracture Zone in the Atlantic (Dick et al., 2008), which nonetheless differ from the Atlantis massif by the absence of olivine-free gabbro but show a high amount of oxide gabbro. Finally, Ocean Drilling Program Leg 209 drilled a series of holes from 14°43' to 15°44'N straddling the 15°20' fracture zone, providing a view of the lithostratigraphy to the south of the 16.5°N core complexes. Notably, gabbro is rare, and the lower crust has a *bimodal* distribution similar to that of the Kane area, with large amounts of troctolite and dunite and oxide gabbro and oxide gabbro-norite the most abundant lithologies. As a whole, the compositional variability of gabbros recovered at OCCs suggests a variable, complex crustal architecture, which emphasizes the need to characterize the lower crust at ridge segments formed at different magma supplies, ridge geometries, and tectonics, as part of interpreting crustal petrogenesis.

This study aims at exploring the architecture and the composition of the lower crust exposed along the 16.5°N region of the MAR. This segment is characterized by a complex detachment fault system developed in a magma-poor regime: unlike the thick gabbroic sections exposed at the Atlantis massif and Atlantis Bank OCCs, and OCCs identified in the 16.5°N MAR region are formed by scattered gabbroic intrusions within a partly serpentinized mantle (Cannat & Casey, 1995; Cannat et al., 1997). This region is characterized by a strong lateral crustal heterogeneity and an active detachment faulting system (Parnell-Turner et al., 2016; Smith et al., 2014). As such, the MAR 16.5°N is similar to the Kane and the 15°20' fracture zones and is an ideal case to explore the petrological processes driving the formation of the lower crust in regions of low magma supply and active detachment. Here we present microtextural observations and major element mineral compositions and discuss the process of emplacement and early deformation histories of these rocks. We use thermodynamic modeling to explore the cause of the bimodal lithological variability of the lower crust in this region, proposing that a close relationship between magma supply, eruption rate, and deformation-driven melt extraction may explain the lithological variability of the lower oceanic crust exposed through detachment faulting.

2. The 16.5°N Region of the MAR

The study area is located between 16° and 17°N and exposes an ~120-km stretch of the slow-spreading Mid-Atlantic Ridge (Figure 1). This region encompasses two spreading segments that strike ~012°, perpendicular to the inferred spreading direction (DeMets et al., 2010). The spreading axis is characterized by a well-developed neovolcanic zone and by a remarkably high rate of teleseismic and hydrophone-recorded

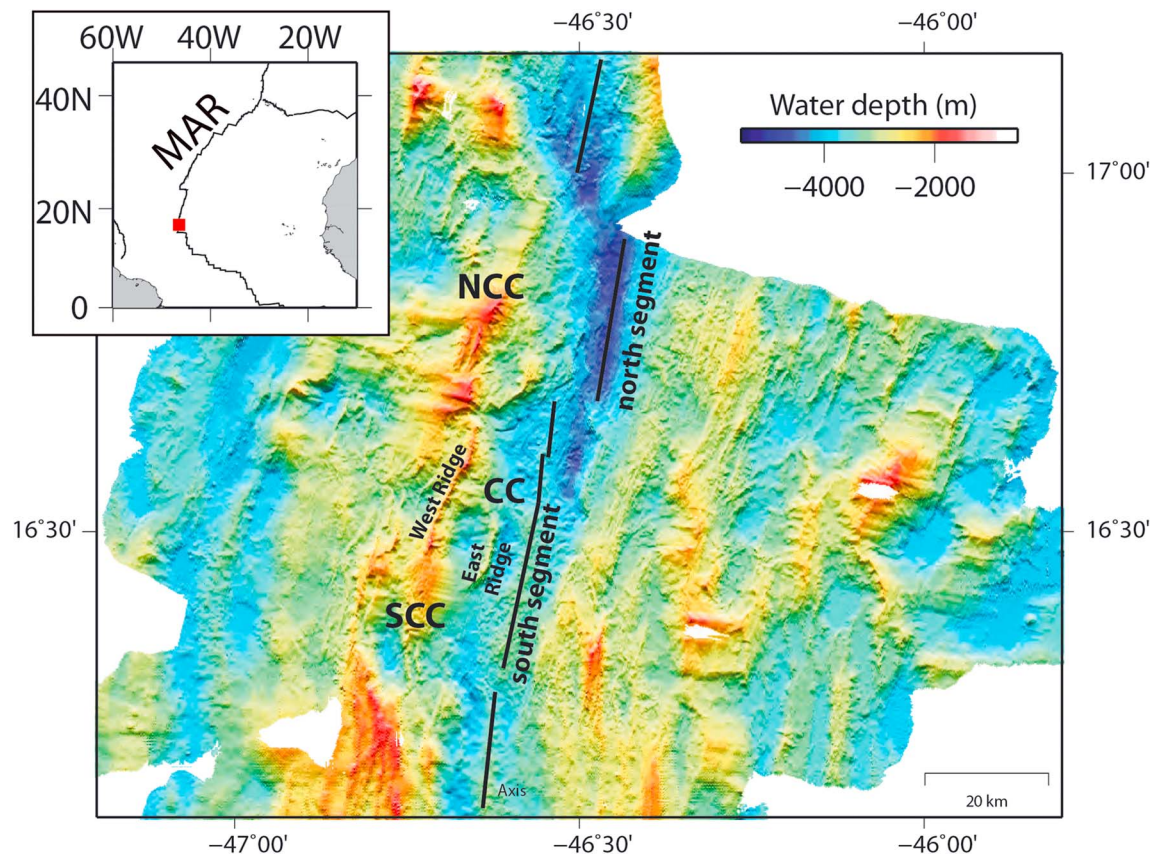


Figure 1. Bathymetric map of the Mid-Atlantic Ridge, 16.5°N area studied by cruise, R/V *Knorr*, KNR210-5 (Smith et al., 2014). The location of southern, central, and northern core complexes are also indicated. SCC = southern core complex; NCC = northern core complex; CCC = central core complex.

seismicity (Smith et al., 2003). The area has also been identified as a region of active detachment faulting, mostly concentrated on the west side of the axis (Escartin et al., 2008).

RV *Knorr* cruise 210 Leg 5 conducted bathymetric, dredging, and autonomous underwater vehicle surveys focused on the neovolcanic zone and western rift mountains (see Parnell-Turner et al., 2018; Smith et al., 2014). Based on the occurrence of corrugated surfaces, different core complexes were identified: (I) the southern core complex, a classic, domed, detachment fault with a slope of 13° and corrugation wavelengths between 400 and 1600 m; (II) the central core complex (CCC), characterized by two distinctive ridge-parallel, linear ridges (east and west ridges, Figure 1), interpreted to be the breakaways of detachment faults that underwent significant rotation (Macleod et al., 2009; Parnell-Turner et al., 2018; Smith et al., 2006, 2008); and (III) The northern core complex (NCC). Compared to the south and central complexes, where the detachment faults intersect the valley floor with a well-developed axial volcanic ridge, the NCC is flanked by a deep axial rift valley, covered by lava flows, but lacking a neovolcanic ridge. This feature suggests that the formation of the NCC was accompanied by limited volcanic activity compared to the southern core complex.

During the RV *Knorr* cruise 210 Leg 5 dredging program, we sampled both the footwall of the detachment faults and the volcanic rocks exposed on the associated ridge axis (72 dredges in total). Overall, ~5,800 kg of basalt, diabase, gabbro (s.l.), and peridotite samples were dredged in 63 locations (see Table S1 of the supporting information). However, the proportions of different rock types vary significantly across the area (Figure 2). Pillow basalt is the most abundant dredged lithology at all the three core complexes. They have been collected from both the crests of the complexes (i.e., detachment breakaway zone) and as the hanging wall debris resting on the detachment fault footwall. Mantle peridotites (harzburgites to dunites) are abundant in the CCC, whereas only gabbroic rocks were collected at the NCC. A very limited amount of gabbroic lithologies (~1 kg in total) were recovered at the SCC and CCC, limited to small intrusions within mantle peridotites. The main characteristics of these areas are reported in Smith et al. (2014) and Parnell-Turner et al.

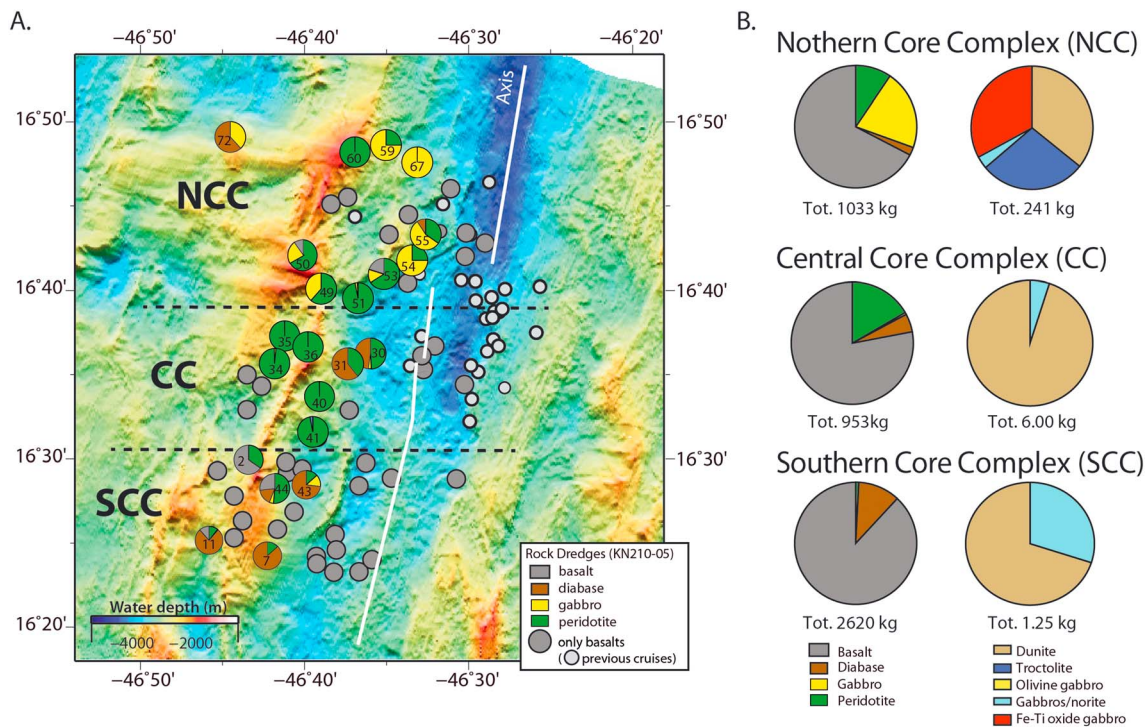


Figure 2. (a) Location of the dredges collected during the cruise, R/V *Knorr*, KNR210-5 (Smith et al., 2014). Large pie diagrams refer to the dredges where gabbros or peridotites were collected; dredge numbers are indicated. (b) Compositional variability of all lithologies and plutonic rocks from southern, central (CCC), and northern core complexes (NCC).

(2018). Here we focus our analyses on the NCC and its surrounding areas, capitalizing on the abundance of gabbroic lithologies there to infer lower crustal formation and evolution.

2.1. Northern Core Complex and Its Surroundings

The gabbros we studied were mainly collected at the NCC. This complex is delineated by a detachment fault, which is locally masked by several rafted blocks of volcanic crust. Smith et al. (2014) suggested that these blocks were produced by short-lived steep-dipping normal faults formed close to the rift axis that merged at depth with the primary detachment fault (see Reston & Ranero, 2011). Each fault block is covered by volcanic hummocks and flows similar to those on the valley floor. The median valley adjacent to the NCC is narrow (3–4 km) and deep (~4,500 m) and is characterized by smooth, likely sedimented surfaces covering flat-topped lava flows and hummocks. Although there is no neovolcanic axial ridge, the occurrence of volcanic ridges and hummocks emerging from the sediments at the west side of the median valley and the flows on the rift valley floor suggest that this segment was volcanically active in the recent past. Several dredges were deployed at the central portion of the NCC, recovered 579 kg of fresh pillow basalts from the terrace of the rafted block (D52, D56, D57, and D65).

The 237 kg of gabbroic rocks were recovered in 10 of 14 dredge hauls (i.e., D49 to D55, D59, D60, D63, D64, D67, D69, D70, and D72) deployed along a ridge around the complex (from the southern shoulder to two narrow ridges in the north). Gabbros in these locations are associated with 157 kg of peridotite sampled in eight dredges and 513 kg of fresh pillow basalts found in six dredges. Dredged gabbros were described macroscopically during the expedition. Each member of the Shipboard Party was responsible for one or more aspects of the description (e.g., rock type, textures, mineral modes, and habits) to ensure consistency throughout the dredged hauls. Only primary minerals were considered to define the initial modal proportion; completely altered rocks are referred to as metagabbros (Table S1 of the supporting information). Representative sample images are displayed in Figure 3. Preliminary onshore analyses followed the shipboard observations in order to test the accuracy of the definition of rock types and deformation intensity. Samples reviewed for the present study provided a good correspondence with the shipboard observation,

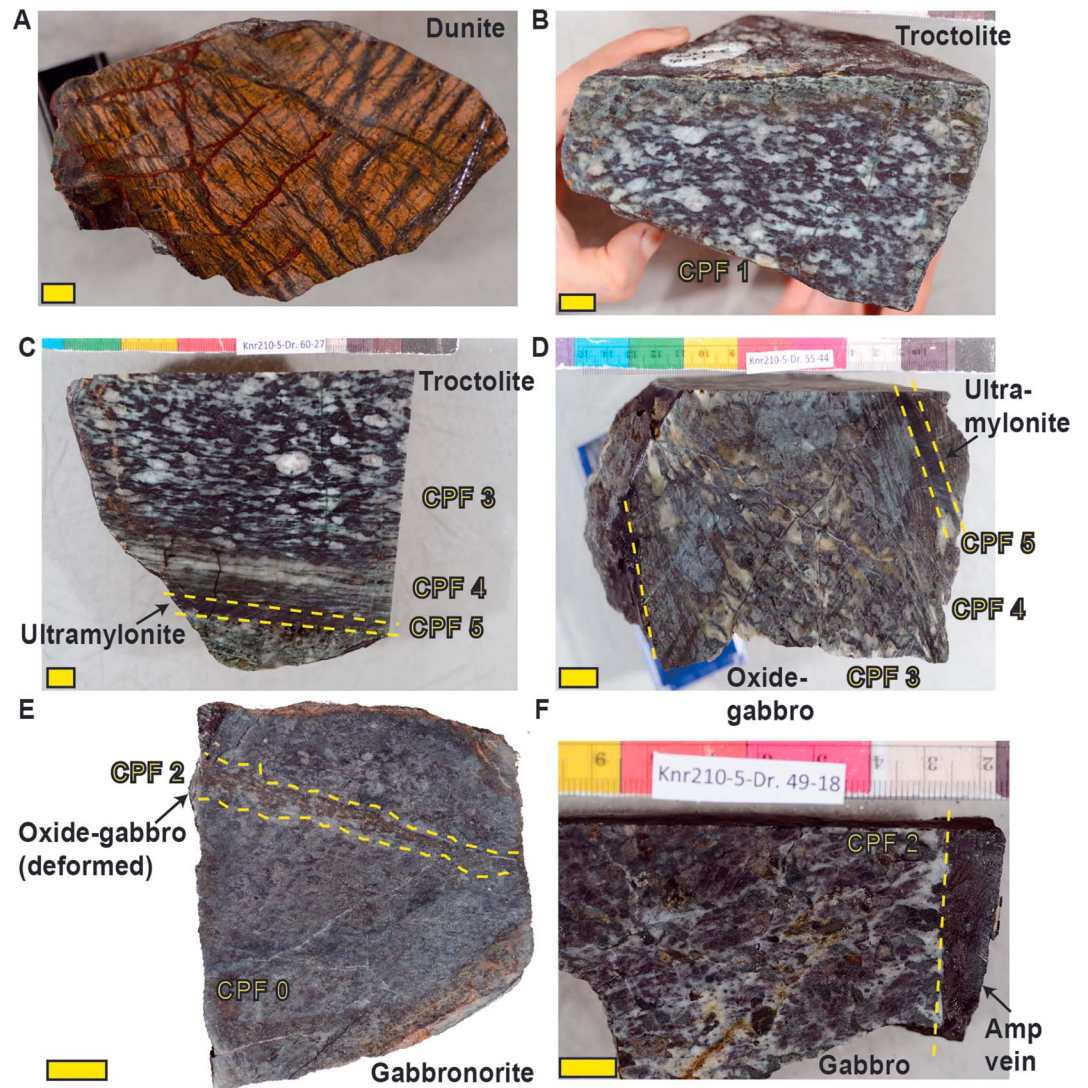


Figure 3. Photographs of cut hand specimens of six different plutonic rocks recovered by dredging during R/V *Knorr* cruise 210-5. Some of the samples show high-temperature crystal-plastic deformation with protomylonitic, mylonitic, and ultramylonitic fabrics. In one case, the high-temperature deformation fabrics are crosscut by lower-temperature brittle fractures and amphibole veins. CPF refers to crystal-plastic fabric as defined in the text.

although minor interstitial phases such as orthopyroxene and amphibole had been commonly underestimated (see textural description). This generally did not affect the classification of the rock types, which is based on major mineral phases. The proportions (wt %) of different gabbroic rocks collected from each dredge are reported in Figure 2, which shows that the lower crust exposed at NCC displays a bimodal distribution, that is, high proportions of primitive plutonic rocks (i.e., dunites and troctolites >60 wt %) associated with evolved gabbroites to oxide gabbros (~30 wt %). Intermediate rocks such as olivine gabbros (olivine >5 vol %; clinopyroxene >10 vol %; oxides <2 vol %) and gabbros in a strict sense (olivine <5 vol %; oxides <2 vol %) and gabbroite (olivine <5 vol %; orthopyroxene >5 vol %) are very limited, as they are to the south. Interestingly, troctolites were mainly collected in two dredges (D59, D60; Figure 2) otherwise characterized by large proportions of serpentinized dunites and pyroxene-bearing peridotites, and by the absence of volcanics. The exposure of mantle peridotites, dunites, and troctolites and the rarity of basalts are typical of sequences thought to represent crust-mantle transitions, such as the OPD Site 895 at Hess Deep (Dick & Natland, 1996), the Adam Dome at the Kane FZ (Dick et al., 2008), the breakaway area of the Godzilla megamullion (Sanfilippo et al., 2013; Sanfilippo, Dick, et al., 2016), and the Uraniwa Hills at the central Indian Ridge (Sanfilippo, Morishita, et al., 2015; Sanfilippo, Morishita, & Senda, 2016).

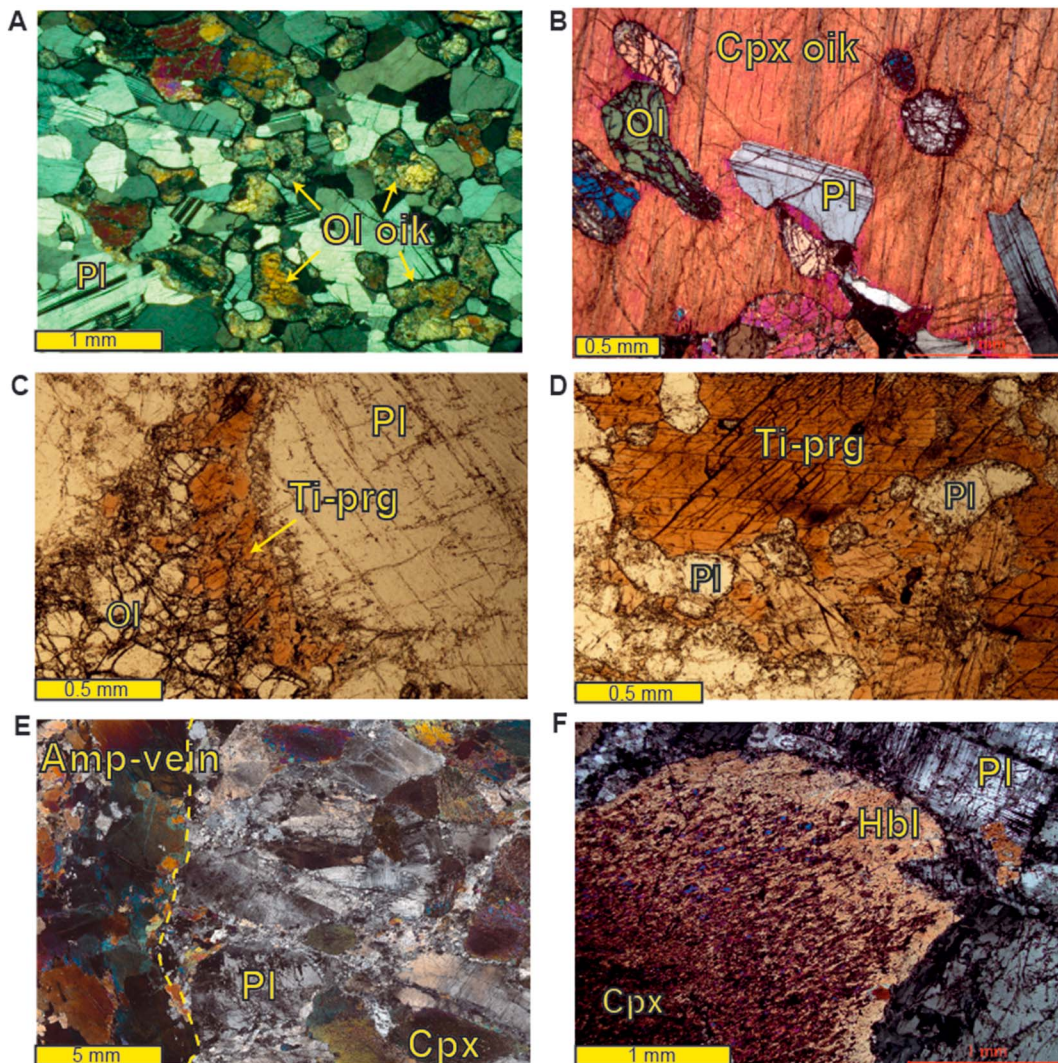


Figure 4. Microphotographs of selected samples. (a) Olivine oikocrysts showing rounded grain boundaries against plagioclase in an undeformed troctolite; (b) large clinopyroxene oikocryst including subrounded olivine and plagioclase chadacryst in a troctolite; Ti-pargasitic amphibole in a sheared troctolite (CPF 1) showing interstitial (c) and oikocrystic (d) habitus; (e) sheared gabbro cut by amphibole vein with diffuse boundaries. Clinopyroxene locally shows partial replacement by amphibole (CPF 2); (f) hornblende corona statically replacing clinopyroxene in the vicinity of the amphibole vein in Figure 4e. Ol = olivine; PI = plagioclase; Cpx = clinopyroxene; Ti-Prg = Ti-pargasite; Hbl = hornblende; CPF = crystal-plastic fabric.

3. Main Petrographic Features of MAR 16.5°N Gabbros

3.1. Igneous Textures

Troctolites have euhedral to subhedral olivine and plagioclase, locally showing subrounded grain boundaries and a poikilitic texture (Figure 4a). Clinopyroxene commonly occurs as films or discrete grains interstitial to olivine and plagioclase. Large clinopyroxene oikocrysts (up to 7 mm) are locally present within the olivine-plagioclase matrix, commonly including euhedral to irregular plagioclase and olivine chadacrysts (Figure 4b). Clinopyroxene oikocrysts show film-like apophyses interstitial to olivine and plagioclase, locally associated with orthopyroxene films. In a few cases, oikocrystic clinopyroxene reaches 10 vol % of the rock, forming spatially defined Ol-gabbro domains. Pargasitic brown amphibole is common within the troctolites as films or interstitial discrete grains locally reaching 0.1 mm (Figure 4c). One troctolite contains large amphibole oikocrysts up to 3 mm. These oikocrysts include rounded plagioclase chadacrysts, having irregular grain boundaries taken as evidence of partial dissolution (Figure 4d). Fe-Ti oxides are locally present in troctolites but are restricted to within the interstitial brown amphibole at the rim of olivine or plagioclase.

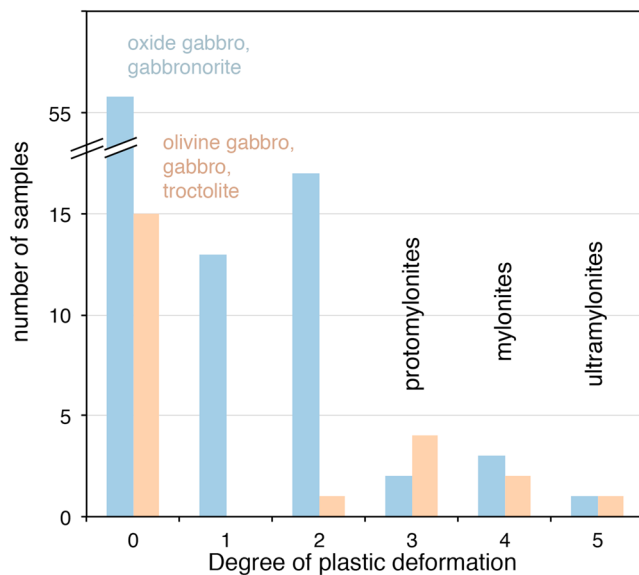


Figure 5. Histogram of deformation intensity of plutonic rocks collected during R/V Knorr cruise 210-5 (see text for detail).

Gabbros and gabbro-norites consist of plagioclase and pyroxenes commonly showing a subophitic texture. Olivine is absent or restricted to small grains (<0.5 mm) rounded in shape. Small (<0.1 mm) irregular grains of Ti-Fe oxides and apatite are locally included in the pyroxenes or at the rim of pyroxene-plagioclase crystals. Orthopyroxene in gabbro-norites occurs in large, subequant crystals with subhedral habit, as distinguished from intergranular rims commonly found in olivine gabbros. Pargasitic brown amphibole is rare in these rocks and present as <0.05 mm-thick films around clinopyroxene.

Oxide gabbros (>2% oxide) have been found as (i) coarse (up to 20 cm)-grained massive samples and as (ii) medium/fine-grained centimeter-sized seams crosscutting either gabbros or gabbro-norites. In both cases, oxide gabbros are mostly constituted by granular plagioclase, clinopyroxene, and locally orthopyroxene, and abundant (up to 15 vol %) Ti-Fe oxides. Olivine is absent from all of these rocks, whereas accessory phases such as zircon and apatite are commonly present. Brown pargasitic amphibole is ubiquitous within the oxide gabbros, occurring as interstitial grains to coronas surrounding opaque minerals or as blebs within partly exsolved clinopyroxene. Coarse-grained oxide gabbros contain irregular oxide-rich patches up to 10-mm wide separating, and in some cases, surrounding aggregates of disrupted plagioclase and clinopyroxene grains. The

oxide-rich domains locally include small plagioclase and/or apatite grains (0.1–0.5 mm), subhedral to rounded in shape. The oxide-gabbro seams are typically found as medium to fine-grained, centimeter-sized layers parallel to the foliation in the host rock. They have a planar aspect and well-defined sutured contacts with the host gabbros, although oxide minerals can be locally dispersed in the host rock a few millimeters from the contact.

3.2. Textures Indicative of High-Temperature Deformation

Metamorphic grade and crystal-plastic fabric intensity were documented for each sample, which were cut perpendicular to the foliation where possible. Approximately 40% of the gabbros preserve textures indicative of shearing and recrystallization under hypersolidus to subsolidus conditions. Deformation intensity was classified on a scale from 0 to 5 (0, *undeformed*; 1, *slightly deformed*; 2, *sheared*; 3, *protomylonitic*; 4, *mylonitic*; and 5, *ultramylonitic*) based on the foliation, grain size, and relative proportions of neoblasts and porphyroclasts. The distribution of the deformation intensity for the different rock types (Figure 5) suggests that the higher-grade crystal-plastic deformation (grades 3 to 5) is equally recorded by primitive and evolved gabbros, while oxide gabbros and gabbro-norites seem to be on average more deformed than troctolites (~50% and ~30% of the total, respectively) at lower grades.

3.2.1. Granulite Grade Deformation

Protomylonites and mylonites generally appear to be indistinguishable on the basis of mineral proportions from their protoliths, which is not the case for ultramylonites (Figures 6a and 6b). Protomylonites are defined by the occurrence of a porphyroclastic texture that locally grades into mylonites having alternating bands of neoblastic plagioclase, olivine, and/or clinopyroxene (Figure 3). The mylonitic zones are up to decimeter wide, although we cannot determinate the original thickness because undeformed portions of the same rock are not recovered. The most common metamorphic assemblage includes recrystallized olivine, pyroxenes, and plagioclase. Depending on the protolith, spinel (in troctolites) or Ti-Fe oxides (in gabbros and oxide gabbros) are also found as neoblastic phases. Olivine, pyroxenes, and plagioclase porphyroclasts are kinked, folded, and displaced by subgrain boundaries. Equant to subequant neoblasts surround porphyroclasts of the same mineral, suggesting subgrain boundary rotation and recrystallization under high-temperature conditions (Hansen et al., 2013; Miranda & John, 2010). Trace amounts of pargasitic amphibole are locally found within the neoblastic assemblage, as small (<0.1 mm) grains in textural equilibrium with the major phases. Samples showing this metamorphic assemblage will be referred to hereafter as *gabbro granulites*, in analogy with the definition of similar rocks from other OCCs worldwide (see Blackman et al., 2006, 2011; Dick et al., 2000, 2008; Hansen et al., 2013; Ildefonse et al., 2007; MacLeod et al., 2017; Miranda & John, 2010).

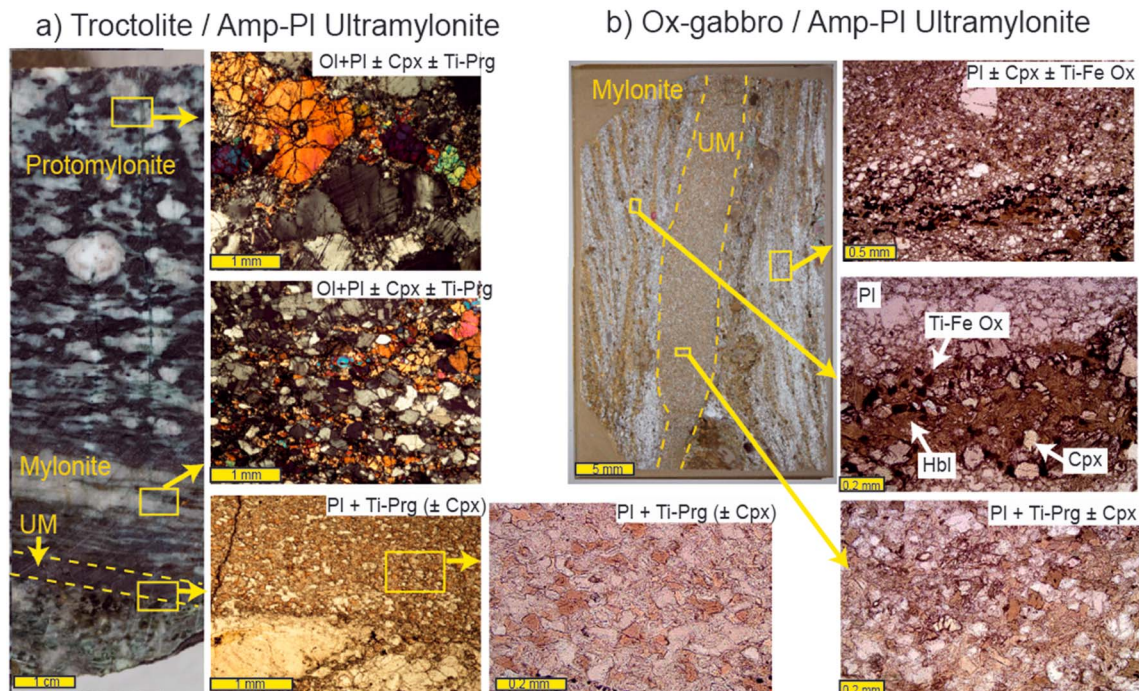


Figure 6. Macroscopic occurrence and microphotographs of the amphibole-plagioclase ultramylonites and host mylonites. (a) Troctolite showing a gradual increase in deformation intensity from protogranular to mylonite to ultramylonite (UM). (b) Scanned thin-section image of the ultramylonite band crosscutting an oxide-gabbro mylonite. Note that the texture and the mineralogical composition of the two ultramylonites are almost identical, although they are developed in highly different magmatic protoliths.

3.2.2. Ultramylonites

The mylonites locally grade into 5- to 10-mm thick, very fine grained (<0.1 mm) ultramylonitic bands. These bands are always found in the median portions of the mylonites and have subplanar shape and sharp boundaries toward the host rock (Figure 3). Unlike the mylonites, which are mineralogically indistinguishable from the magmatic protolith, the ultramylonites have a distinct mineralogical composition. We found ultramylonites developed from different protoliths ranging from troctolites (Figure 6a) to oxide gabbros (Figure 6b). These two end-members will be described hereafter.

- Figure 6a shows a ~5-mm-thick ultramylonite located within a troctolite mylonite. The host protomylonite and the mylonite are formed by olivine and plagioclase porphyroclasts mantled by a neoblastic assemblage of plagioclase and olivine, locally including clinopyroxene and brown amphibole (Ti-pargasite). Spinel porphyroclasts are also present and partly recrystallized along the main foliation planes. In contrast, olivine and spinel are absent in the ultramylonite band, which is mainly formed by a very fine grained (<0.1 mm) assemblage of plagioclase and brown amphibole (Ti-pargasite) and rare clinopyroxene. Both clinopyroxene and brown amphibole are locally replaced by green amphibole and chlorite in a coronitic texture.
- Figure 6b shows an up to ~5-mm-thick ultramylonite band located within an oxide-gabbro mylonite. The host mylonite is characterized by plagioclase and clinopyroxene porphyroclasts immersed in a neoblastic assemblage of plagioclase, clinopyroxene, and Ti-Fe oxides (~5–10 vol %). Pale to green amphibole (hornblende) statically replacing the neoblastic clinopyroxene is abundant, whereas brown amphibole is absent. In contrast, the ultramylonite band is characterized by a very fine grained assemblage of plagioclase and brown amphibole (Ti-pargasite) locally associated with minor clinopyroxene, and by the absence Ti-Fe oxides. Similar to the ultramylonite located in the troctolite, green amphibole and chlorite locally replace the brown amphibole and the clinopyroxene.

Taken as a whole, despite the fact that the two ultramylonites developed from different magmatic protoliths, the ultramylonites are texturally and mineralogically indistinguishable, consisting of a fine-grained neoblastic assemblage of plagioclase, brown amphibole, and, more rarely, clinopyroxene.

3.3. Textures Indicative of High-Temperature Alteration

Deformed gabbros locally show traces of alteration at high-temperature conditions (amphibolite facies). This process is mainly indicated by (i) the occurrence of amphibole-rich veins crosscutting the foliation in the host gabbros at high angle; (ii) the occurrence of pale-brown amphibole (hornblende) statically replacing the clinopyroxene. These textures are well exemplified in Figure 3f, which shows a sheared gabbro-norite crosscut by an undeformed amphibole-rich vein, at high angle with the main foliation in the host rock. Hornblende in the veins shows a fibrous texture and is elongated parallel to the vein wall. Plagioclase close to the contact with the vein is statically recrystallized in a fine-grained assemblage. Clinopyroxene in the host gabbro is almost totally replaced by single grains or aggregates of hornblende spatially locally associated with very fine grained (<0.05 mm) albitic plagioclase (Figure 3f). Similar textures are also found where irregular veins cross-cut the gabbros, leading to the formation of hornblende at the expense of clinopyroxene, and fine-grained plagioclase replacing the coarse plagioclase of magmatic origin. In almost all of the samples, hornblende is locally rimmed or partially replaced by green amphibole and chlorite, as a response to lower-temperature greenschist facies alteration.

4. Major Element Mineral Compositions

Major element mineral compositions of selected 16.5°N gabbros were obtained using a JEOL JXA-8200 electron microprobe (Dipartimento di Scienze della Terra, Università degli Studi di Milano, Italy) at 15-kV accelerating voltage and 15-nA beam current. Counting time was 30 s on the peak and 10 s on the backgrounds. Natural silicates were utilized as standards, and data reduction was carried out using the CITZAF package. Undeformed and variably deformed samples ranging from troctolites to oxide gabbros were selected for the microprobe study, in order to cover the main chemical variability of the rock types. Representative analyses of olivine, plagioclase, pyroxene, and amphibole of selected samples are reported in supporting information Tables S2–S6. Four samples were also mapped using a Zeiss Sigma HD field emission gun scanning electron microscopy (FEG-SEM) installed at Cardiff University. This machine is equipped with dual 150-mm^2 Oxford Instruments X-Max^N energy dispersive silicon drift detectors, which enable high count rates ($>1,000,000$ cps) to be obtained. The data were background corrected using Oxford Instruments AZtec software prior to the production of element maps.

Olivine in troctolites has high forsterite (Fo) contents (86 to 88 mol %) and relatively constant NiO (0.20–0.25 wt %) and MnO (0.19–0.25 wt %) contents. There is no compositional difference between porphyroclastic and neoblastic olivine. Plagioclase anorthite content varies from An_{81} in troctolites to An_{46} in oxide gabbros. Chemical analyses and element maps clearly show that high-temperature deformation is associated with a decrease in anorthite in plagioclase neoblasts compared to porphyroclasts in the same rock. This is well illustrated in Figure 7a, where compositional maps for Na contents of a sheared troctolite are shown. In particular, the lower Na (and higher Ca, not shown) of the fine-grained neoblasts clearly indicates lower An contents (~ 78 mol %) compared to that of the porphyroclasts (~ 81 mol %). Similarly, an even greater variation in plagioclase anorthite component characterizes the troctolite mylonite-ultramylonite association (Figure 7b). Here the plagioclase in the ultramylonite has lower Ca (and higher Na) compared to that in the mylonite, resulting in a decrease from An_{81} in the mylonites to An_{65} in the ultramylonite. A unique exception is represented by the mylonite-ultramylonite association in the oxide gabbro-norite (Figure 7c), where compositional maps show higher Ca and lower Na contents of the plagioclase in the ultramylonite (An_{82}) compared to that in the host mylonite (46 mol %). Finally, a decrease in anorthite component is apparent in recrystallized plagioclase associated with the formation of the amphibole-rich vein in Figure 7d. Here the neoblastic plagioclase at the amphibole vein/gabbro contact and the plagioclase in the vein has higher Na and lower Ca compared to the plagioclase porphyroclasts, resulting in An_{53} for the former and $\sim \text{An}_{58}$ for the latter. Note that very high Na and low Ca characterize the fine-grained plagioclase associated with veins and microcracks crosscutting the magmatic phases (An_{20} to An_{25}).

Clinopyroxene shows a wide compositional range with Mg\# ($100 \times \text{Mg}/(\text{Mg} + \text{Fe})$) varying from 89 in oikocryptic clinopyroxene in troctolites to 65 in oxide gabbros. Clinopyroxene in troctolites is distinct from that in gabbros by generally higher Cr_2O_3 and Al_2O_3 contents (0.4–1.5 wt % compared to <0.2 wt % in the gabbros) but high TiO_2 contents (Figure 8). Chemical mapping suggests that clinopyroxene neoblasts in sheared to mylonitic rocks are nearly indistinguishable from the porphyroclasts in the same sample. The only exception is the

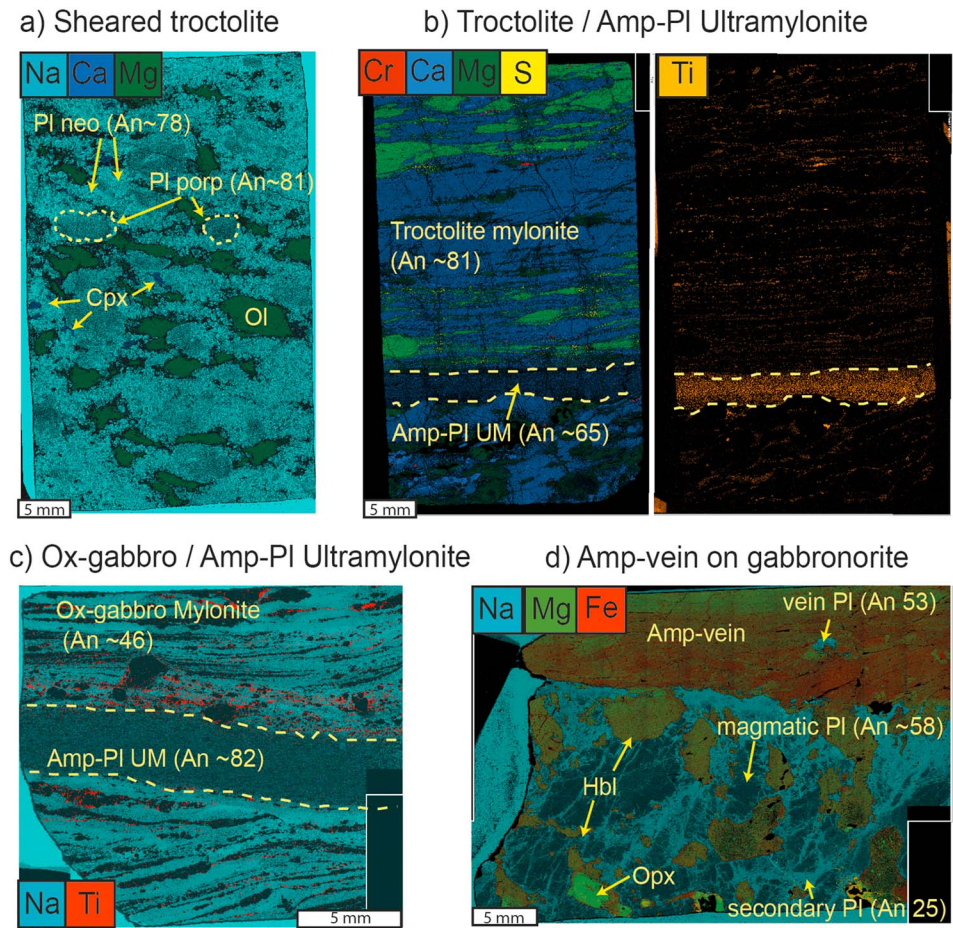


Figure 7. FEG-SEM compositional maps of selected samples. (a) Na, Ca, and Mg map of a sheared troctolite clearly showing an increase in Na and decrease in Ca in the neoblastic plagioclase compared to the coexisting porphyroclasts. (b) Cr, Ca, Mg, S, and Ti maps of the troctolite mylonite including a Amp-PI ultramylonitic band. The maps show a decrease in Ca in plagioclase in the ultramylonite compared to the mylonite and the distribution of Ti-bearing phases (i.e., amphibole) and Cr-bearing phases (i.e., spinel) between the two lithologies. (c) Na and Ti map of the oxide-gabbro mylonite including a amphibole-plagioclase ultramylonitic band. The maps show a sharp decrease in Na in plagioclase in the ultramylonite compared to the mylonite and the lack of Ti-Fe oxides in the ultramylonite. (d) Detail of a Na, Mg, and Fe map of a gabbro crosscut by an amphibole vein. Note that hornblende replacement is widespread in the vicinity of the amphibole vein, and that Na-rich plagioclase is associated with microcracks and late fractures.

clinopyroxene in oxide-gabbro mylonites/ultramylonite shown in Figure 7c, which has a sharp change in chemical composition from the mylonite ($Mg\# = 64\text{--}67$; $Cr_2O_3 = 0.01\text{--}0.02$ wt %) to the ultramylonite ($Mg\# = 73$; $Cr_2O_3 = 0.5$ wt %). With the exception of this ultramylonite, there is a positive correlation between $Mg\#$ in clinopyroxene and anorthite content in coexisting plagioclase from each sample (Figure 9a).

Orthopyroxene $Mg\#$ is well correlated with $Mg\#$ of coexisting clinopyroxene (Figure 9b). Similar to clinopyroxene, orthopyroxene from our sample suite is characterized by (i) high $Mg\#$ and Cr_2O_3 contents (87–89; 0.4–0.6 wt %, respectively) in troctolites and progressively lower (75–58; 0.01–0.04 wt %) in gabbro/gabbroonorite/oxide gabbro, and (ii) lack of correlation between TiO_2 and $Mg\#$. The composition of the coronitic to interstitial orthopyroxene in the troctolites suggests a magmatic rather than a metamorphic origin, similar to the granular orthopyroxene in the gabbroonorites.

Amphibole is a ubiquitous phase in our samples. There is a clear chemical distinction between the green to pale-brown amphibole statically replacing clinopyroxene (Type I) and the brown amphibole forming poikilitic to interstitial grains in undeformed samples or found as neoblasts within the granulites (Type II; Figure 10). Type-I amphibole occurs in two forms: (i) green amphibole with very low Al^{IV} (<0.39 atoms per formula unit, apfu), TiO_2 (<0.41 wt %), and alkalis ($[K + Na] < 0.12$ apfu), mainly consisting in actinolite and tremolite

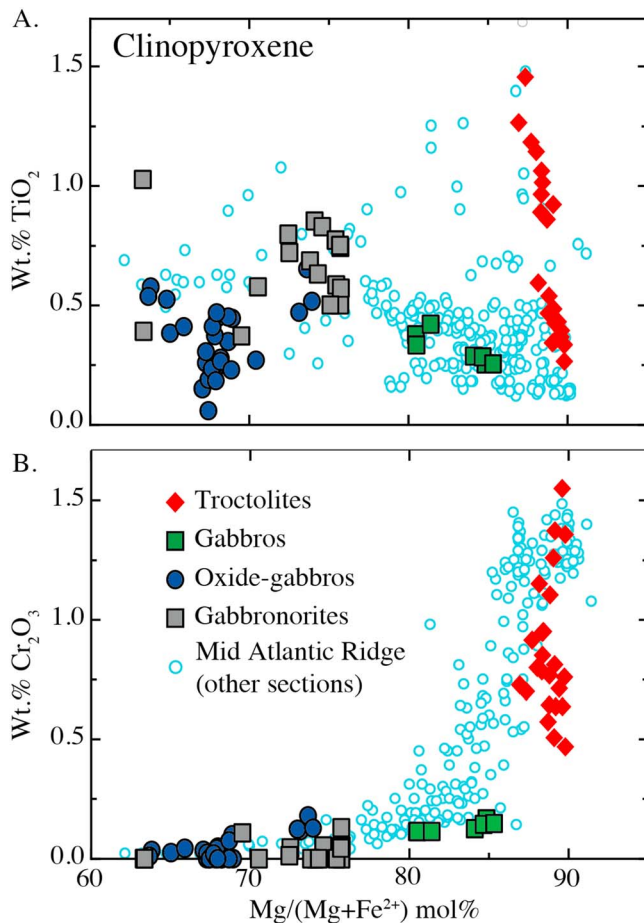


Figure 8. Variations in TiO_2 (a) and Cr_2O_3 (b) versus $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ (mol %) in clinopyroxenes from the 16.5°N gabbros. Symbols are grouped per rock type and indicate single spot analyses (core and rim). The composition of clinopyroxenes from gabbros from other lower crustal sections exposed along the Mid-Atlantic Ridge is also depicted (Coogan et al., 2000; Dick et al., 2010; Drouin et al., 2009; Lissenberg & Dick, 2008; Nonnotte et al., 2005; Ross & Elthon, 1993; Suhr et al., 2008).

rocks such as olivine-gabbros and gabbro in a strict sense are restricted to <3 wt % of the ~356 kg of gabbros sampled in the region (Figure 2). This bimodal distribution is remarkably different to that of the gabbroic section drilled at Hole U1309D (Blackman et al., 2006, 2011), formed in a relatively robust magmatic center along the MAR (Godard et al., 2009). It also contrasts sharply with the Atlantis Bank gabbro massif on the SW Indian Ridge, which is dominated by moderately fractionated olivine gabbro that grades into subordinate highly evolved oxide gabbros (e.g., Dick et al., 2000; MacLeod et al., 2017). Motivated by the similarity of the gabbros exposed in the 16.5°N region with those of the Kane megamullion and in the vicinity of the 15°20' fracture zone, hereafter we examine how magma supply and melt extraction may control the overall composition of the crustal sections exposed through detachment faulting. We calculate the relative amount of different gabbroic lithologies (i.e., dunites, troctolites, olivine gabbros, gabbros, and oxide gabbros) crystallized during a fractional crystallization process using the thermodynamic program *MELTS* (Ghiorso et al., 2002; Ghiorso & Sacks, 1995). In order to take into account that part of the initial liquid mass is erupted as basalt on the seafloor, we performed this calculation in different steps, allowing a proportion of the liquid to be subtracted at each step of the crystallization process (parameters and results of the model in Tables S7–S9 of the supporting information). The starting liquid (*Liq 0*) is a primary melt formed by ~10% melting of a depleted MORB mantle peridotite source ($\text{Mg\#} \sim 72$; Kinzler & Grove, 1993). After a defined amount of differentiation (for the sake of simplicity fixed at $\Delta\text{Mg\#} \sim 4$), a precise mass of liquid (*Liq 1*) is subtracted and the remaining

(Figure 10); (ii) pale-brown amphibole, having higher Al^{IV} (0.83–1.29 apfu), TiO_2 (0.3–1.4 wt %), and alkalis (0.49–0.78 apfu) and mostly represented by hornblende (Figure 10b). Pale-brown hornblende also constitutes the amphibole-rich veins. These amphiboles have Al^{IV} (1.24–1.41 apfu) and alkalis (0.51–0.82 apfu) partly overlapping those in the amphibole coronas but have higher TiO_2 contents (3.0–3.3 wt %). TiO_2 contents of the hornblende in the vein decrease toward the rim. Chlorine in hornblende coronas and hornblende in veins varies between 0.1 and 0.2 wt % (Figures 10b and 10c).

In contrast, Type-II amphibole is brown to reddish brown and mostly consists of Ti-pargasite. Within the undeformed troctolite and gabbro samples, this amphibole has high Al^{IV} (1.74–1.82 apfu) and alkalis (0.61–0.79 apfu) and very high TiO_2 contents (4.2–4.9 wt %) and high Mg\# (Figure 10d). Chlorine is lower than the detection limit of the microprobe analyses (~0.1 wt %; Figures 10b and 10c). Similar to the hornblende in the amphibole veins crosscutting the gabbros, the large amphibole oikocryst in troctolites shows a sharp decrease in Al^{IV} and TiO_2 from the core toward the rim. Amphibole neoblasts in mylonites and ultramylonites are chemically similar to the magmatic amphibole in undeformed samples. They have high Al^{IV} (1.50–1.82 apfu) and alkalis (0.62–1.80 apfu), low chlorine (<0.1 wt %), and highly variable TiO_2 contents (1.5 to 4 wt %). The neoblastic amphiboles in the two ultramylonites are overall similar to both the magmatic amphibole and the neoblastic amphibole in the mylonite. The amphibole in the troctolitic ultramylonite tends to have higher Al^{IV} and TiO_2 contents and Mg\# than the amphibole in the oxide-gabbro ultramylonite (Figures 10b and 10d).

5. Discussion

5.1. Bimodal Distribution of Gabbros From the 16.5°N Region of MAR: A Quantitative Model to Explain the Compositional Variability of the Lower Oceanic Crust

The composition of the gabbroic rocks collected from the 16.5°N region of the MAR indicates a lower oceanic crust most likely formed by scattered intrusions of chemically primitive gabbros (i.e., troctolites), mainly associated with evolved gabbronorites and oxide-rich gabbros. Intermediate

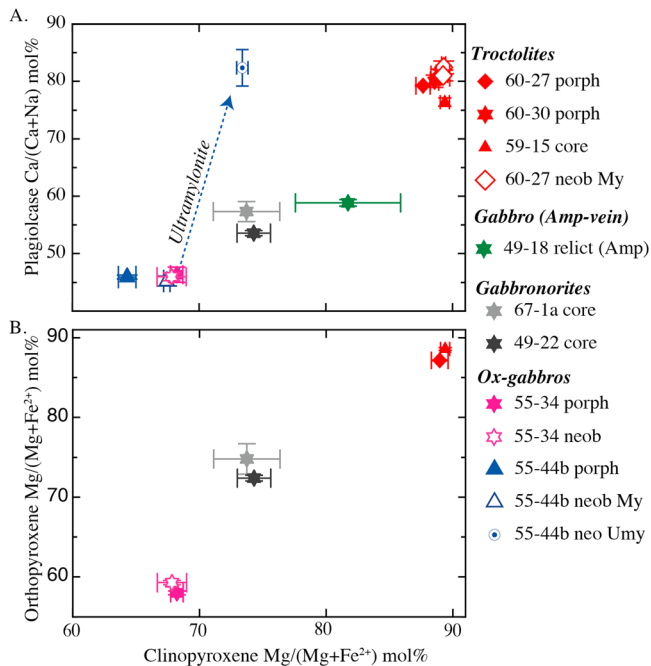


Figure 9. Covariations in clinopyroxene $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ (mol %) versus $\text{Ca}/(\text{Ca} + \text{Na})$ (mol %) in plagioclase and $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ (mol %) in orthopyroxene coexisting in selected gabbros. Dashed arrows indicate the chemical variation in clinopyroxene and plagioclase in the ultramylonite compared to the host oxide-gabbro mylonite. Data are averaged per sample; error bars represent one standard deviation of the mean value.

composition of *Liq 1* is used as initial composition for the next step of differentiation. The mass of liquid subtracted is calculated by scaling the melt mass in proportion to the compositional distribution of the erupted basalts, which is thereby a fundamental input of our model. We cannot use the observed compositional variability of basalts sampled exclusively in the 16.5°N region, considering that the genetic relationships between the basalts along axis and the gabbros exposed through detachment faulting is not obvious and that basalt sampling is inevitably fragmentary. It has been previously noted that the compositional distribution of basalts at mid-ocean ridges is globally dependent on the spreading rates (Melson et al., 1976; Sinton & Detrick, 1992). In particular, basalts erupted at slower-spreading ridges tend to be more primitive compared to those erupted at fast-spreading ridges (Figure 11). The large-scale compositional variability of the basalts can thereby be considered meaningful and allows us to compare the results of our model with different lower crustal sections exposed along the same ridge segment. Here we used the overall compositional distribution of the basalts erupted along the 10–35°N segment of the MAR, which comprises ~2,700 glass analyses selected from the PetDB database (reference Lehnert paper), making the necessary assumption that the distribution is constant for all the modeled scenarios. An explanation of the model is reported in Figure 12.

The solid composition is calculated at each step from the total mass of crystallizing phases given by the program (Figures 13a and 13b). The crystallizing phases are restricted to olivine, plagioclase, clinopyroxene, and Fe-Ti oxide, following the fractionation trends inferred for a Mid-Ocean Ridge basalt (MORB) melt. Minor phases such as orthopyroxene and amphibole are not considered in the model because they occur as interstitial

phases, likely related to crystallization from intercumulus melt. This is in contrast to the primitive orthopyroxene-bearing cumulates that have been sampled in different locations along the mid-ocean ridge system. The orthopyroxene from these rocks has primitive compositions and may represent crystallization from melts more depleted than typical MORB (e.g., Ross & Elthon 1993) either derived from melting a hydrated mantle (Nonnotte et al., 2005) or from melt residual by interaction with mantle peridotites (see also discussion in Gillis et al., 2014). However, it should be noted that gabbronorites having granular orthopyroxene as a cumulus phase were rarely sampled in this study, and that these rocks do not contain olivine and have relatively evolved mineral compositions, plotting in the field of the orthopyroxene-free gabbros (Figures 8 and 9). For the sake of simplicity, we hence grouped the gabbronorites with the gabbros in a strict sense in our model. The total mass of initial liquid subtracted by eruption (M_e) with respect to that crystallized (M_c) is referred to as M_e/M_c . At $M_e/M_c = 0$ the melt is totally retained in the lower crust, and the mass of gabbro crystallized corresponds to that of pure fractional crystallization. At high M_e/M_c the melt is preferentially erupted, and the relative mass of crystallized gabbros decreases.

The proportion (mass %) of gabbros crystallized at different M_e/M_c (0 to ~7:3) is shown in Figure 13, where the chemical and modal compositions of the crystallizing assemblages and the distribution of the resulting erupted basalts are shown at steps of $\Delta\text{Mg}\#$ 4. Remarkably, the olivine and clinopyroxene crystallized from the computed melt fit the composition of the natural samples from this study very well. As was expected, this model shows that at increasing M_e/M_c , a large proportion of the melt is erupted on the seafloor during the first phase of crystallization. Hence, the crystallizing assemblage tends to be progressively more primitive, that is, olivine \pm plagioclase assemblages are preferentially formed until the melt is exhausted (Figure 13e). At the same time, at high M_e/M_c ratios most of erupted melts are restricted to basalts with very primitive compositions.

This simple scenario is highly improbable, however, as it implies that the liquid mass is entirely extracted from the cumulate at each step of differentiation. Studies of oceanic gabbros indicate that variable amounts of interstitial melt are retained within the crystal mush (e.g., Meyer et al., 1989; Natland & Dick, 2001). Hence,

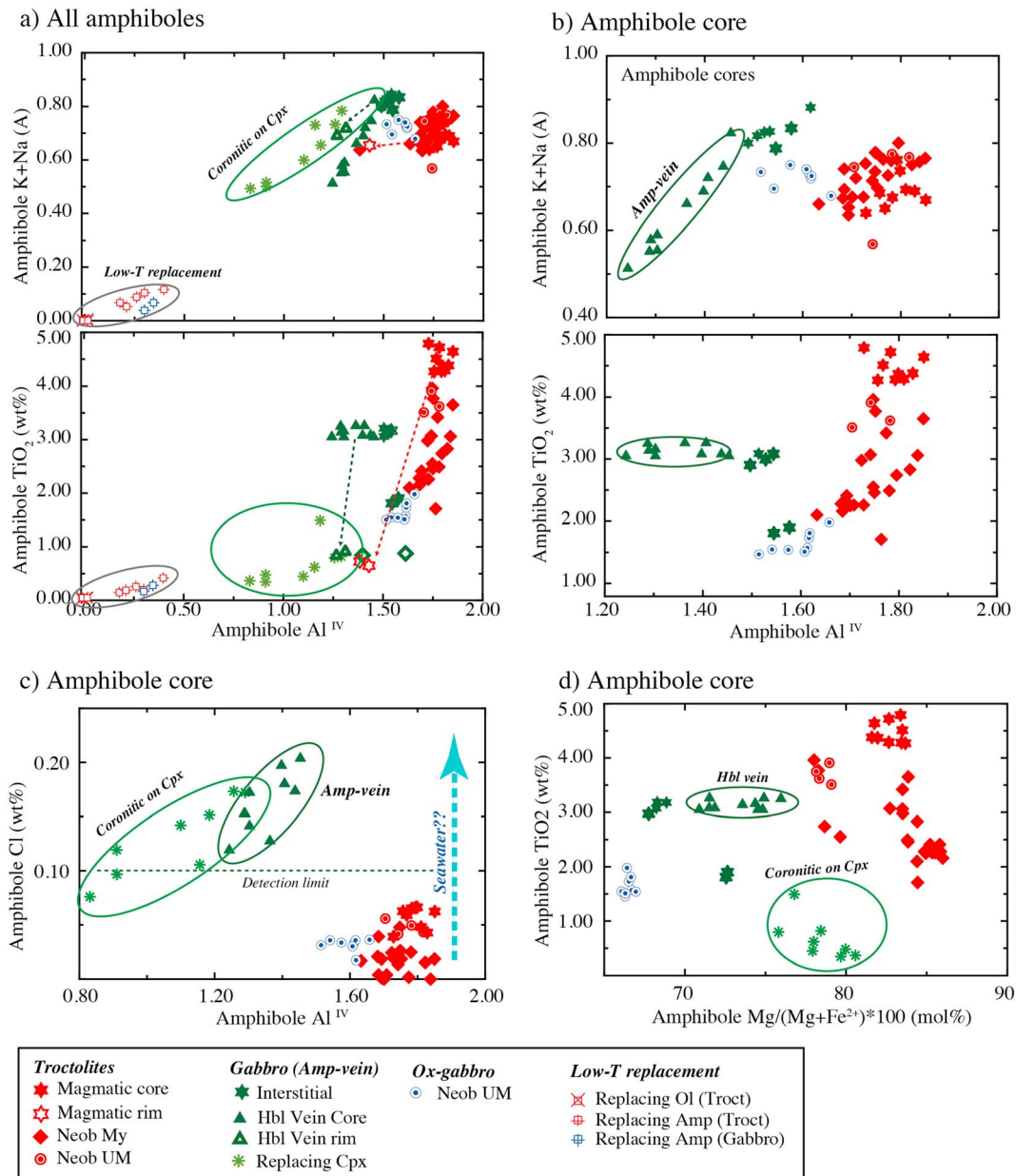


Figure 10. Compositions of amphibole from selected gabbros. (a) Variations in alkali (Na + K) and TiO₂ (wt %) versus Al^{IV} (apfu) in amphibole from selected gabbros. (b) Same plot as Figure 10a including only core analyses of pargasite and brown hornblende. (c) Chlorine (wt %) versus Al^{IV} (apfu) in amphibole; detection limit of electron microprobe analyses is also indicated. (d) Variations in TiO₂ (wt %) versus Mg/(Mg + Fe²⁺) (mol %) in pargasite and brown-hornblende (core analyses). Each symbol represents a single spot analysis.

we assume that a proportion of the initial melt is retained at each step of the crystallization process, following a separate liquid line of descent (see Figure 12). We must consider that the interstitial melts can crystallize within the cumulus matrix at the closure of the magmatic system (e.g., Borghini & Rampone, 2007; Tribuzio et al., 2000) or can migrate through the crystal mush driven by buoyancy differences or by compaction (e.g., Dick et al., 2000; Natland & Dick, 2001). In both cases, textural and geochemical evidence in gabbros suggest that these melts tend to partly assimilate the crystal matrix, causing geochemical modification ascribable to assimilation-fractional-crystallization (AFC) processes (e.g., Borghini & Rampone, 2007; Coogan et al., 2000; Drouin et al., 2009; Gao et al., 2007; Lissenberg & Dick, 2008; Lissenberg & MacLeod, 2016; Sanfilippo et al., 2013). The chemical response to these processes has been modeled following equations from DePaolo (1981). These equations replicate the variations in trace element compositions of

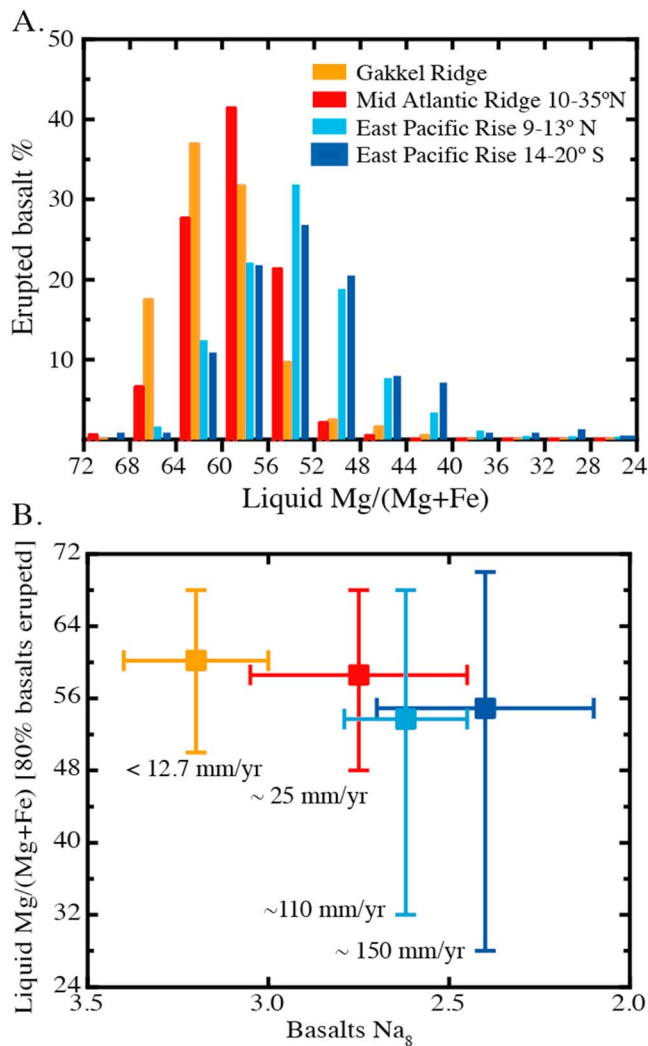


Figure 11. (a) Compositional distribution of basalts from Gakkel ridge (~500 glass analyses); Mid-Atlantic Ridge 10–35°N (~1,300 glass analyses); East Pacific Rise 9–13°E and East Pacific Rise 9–13°N (~230 glass analyses), and East Pacific Rise 14–20°N (~1,050 glass analyses). Data are compiled from PetDB (Lehnert et al., 2000). (b) Average compositions and standard deviation of Na₈ (Klein & Langmuir, 1987) versus Mg/(Mg + Fe) of the basalts in Figure 11a. The average full spreading rates of the regions are also indicated (see also Coogan, 2007; Sinton & Detrick, 1992).

the reacting melts and of the phases crystallized from it (see Borghini & Rampone, 2007; Coogan et al., 2000; Gao et al., 2007; Lissenberg et al., 2013; Lissenberg & MacLeod, 2016; Sanfilippo, Morishita, et al., 2015). They have been successfully used to test AFC hypotheses in well-constrained melt-rock reaction scenarios, such as the conversion of dunite to troctolite (e.g., Rampone et al., 2016, and reference therein) or troctolite to olivine-gabbro (Lissenberg & Dick, 2008). When applied to the scale of the entire oceanic crust, a process of assimilation would introduce a number of independent variables (i.e., the modal amount of mineral phases involved, the chemical compositions of the reactants, and the mass assimilate/mass crystallized ratios; see discussion in Lissenberg et al., 2013). Such a model could not be reproduced by the *MELT* model used here.

As a simplification, at each step we subtracted a certain amount of melt proportional to the melt density (Figure 13d), considering that a maximum of 30% of liquid can initially be trapped in the solid framework before migrating upward due to compaction by density-driven flow (Meyer et al., 1989; Morse, 1979). Then we calculate the gabbros crystallized from the total mass of trapped melts (Figure 12). The mass of gabbro resulting from this calculation was then added to that of the gabbros previously obtained. Note that owing to an increase in melt density with the chemical evolution, our model supposes that the amount of melt potentially trapped in the crystal framework increases at decreasing liquid Mg#. This causes a dependence of the amount of trapped melt on the M_e/M_c ratio, with a more extensive melt entrapment occurring at low M_e/M_c ratios (Figure 13e).

As expected, this calculation shows that the relative amount of evolved lithologies (mainly oxide-gabbro) increases in all the modeled scenarios (Figure 13e). In particular, at high M_e/M_c ratios, most of the initial liquid is erupted on the seafloor before the melts reach saturation in clinopyroxene, thereby preventing the formation of moderately evolved gabbros (olivine-gabbros and gabbros in a strict sense). However, at the same time, the occurrence of trapped liquid enables the local formation of evolved lithologies as this melt migrates due to upward compaction and lateral density-driven flow (gabbro-norites to oxide gabbros). As a consequence, at high M_e/M_c ratios the model is able to produce a bimodal distribution of the gabbros, characterized by large proportions of primitive lithologies and lack of intermediate compositions.

It is noteworthy, however, that the model fails to reproduce the large amount of oxide gabbros present in the 16.5°N region. There are several factors that can account for this. Most oxide gabbros appear to be formed

by interstitial melts expelled from the cumulate matrix and by upward compaction and/or high-temperature deformation into narrow zones of the crystal mush often associated with shear zones along the detachment fault surface (Dick et al., 2000; MacLeod et al., 2017; Natland & Dick, 2001). Moreover, it has been recently argued that the Atlantis Bank gabbroic massif is laterally zoned to more evolved cumulates that comprise the entire section from the base of the crust to the dike-gabbro transition at the distal end of the body near the Atlantis II Transform (MacLeod et al., 2017). This shows that density-driven lateral flow by either direct intrusion or permeable flow plays a major role in the architecture of the lower oceanic crust. Thus, as seen at the Kane megamullion (Dick et al., 2008) and Atlantis Bank (MacLeod et al., 2017), while dunite and troctolitic dikes are rare in mantle massifs adjacent to major magmatic centers at slow spreading ridges, oxide-gabbro dikes are widely distributed lithology. Thus, the amount of oxide gabbros can be biased by dredging and drilling in areas of low magma flux, with highly centralized magmatic centers and intervening relatively amagmatic regions, as from 13° to 17°N on the MAR (e.g., Mendel et al., 1997; Sauter et al., 2001; Standish et al., 2008). Finally, we emphasize that any AFC process would tend to increase the incompatible element

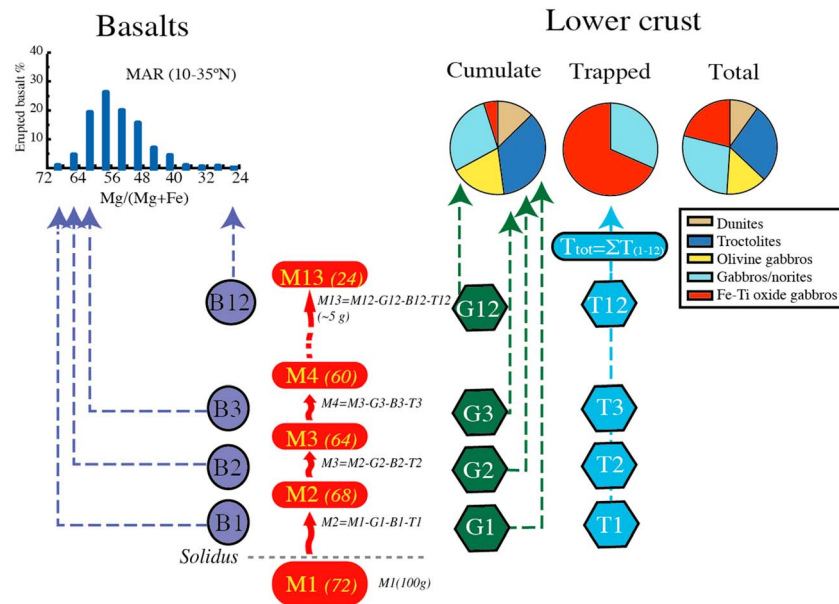


Figure 12. Visual explanation of the quantitative model. M1 is the primary melt with $\text{Mg}/(\text{Mg} + \text{Fe}) \sim 72$ and mass 100 g. M2 to M13 are melts produced by the model at steps of $\text{Mg}\# \sim 4$. The mass of melt at each step is calculated as indicated by the italic numbers. B1 to B12 are melt extracted at each step of the model. Their mass is scaled to reproduce the actual compositional variability of melts erupted at the MAR (10–35°N). G1 to G13 are gabbros produced by the model and forming the *cumulate*. T1 to T12 are melts trapped at each step and subtracted from the total melt mass. T_{tot} is the sum of T1 to T12 and is used to calculate the proportion of gabbros crystallized from trapped melts (*trapped*). The *Total* lower crust composition is given by the sum of gabbros crystallized as *cumulate* + *trapped* (see text for details).

composition of the interstitial melt (see Lissenberg & MacLeod, 2016, and reference therein), producing melts anomalously enriched in incompatible elements compared to a melt evolving through fractional crystallization. This suggests that a melt produced by AFC would potentially enriched the melt in Ti, bringing the saturation in Fe-Ti oxides forward and producing higher amounts of oxide-bearing lithologies. This is another possible reason why our model seems to underestimate the amount of oxide-gabbros compared to the natural occurrences.

Although fairly simplistic, in combination with insight provided by field mapping into ocean crust architecture, this model provides insight into why a bimodal distribution of the lower oceanic crust may be expected in regions where a high proportion of liquid produced in the mantle is erupted on the seafloor, with a minor proportion of intrusive rocks. This scenario recalls the *plum-pudding model* suggested for slow-spreading ridges (Cannat, 1993; Cannat et al., 1997; Cannat & Casey, 1995), which proposes that the lower oceanic crust might consist of small gabbroic plutons scattered within the lithospheric mantle (see also Dick et al., 2008, 2010; Kelemen et al., 2007).

The outcomes of our model are consistent with the compositional heterogeneity of the lower oceanic crust along the MAR (Figure 13). For instance, a lower oceanic crust mainly consisting of primitive gabbros and highly evolved lithologies is expected at regions characterized by scattered injections intruded within mantle peridotites, such as the region considered here or the 15°20'N fracture zone drilled during Leg 209 (Kelemen et al., 2007). On the other hand, a lower oceanic crust mostly composed of moderately evolved gabbros associated with primitive lithologies (troctolites and dunites) and minor oxide gabbro is expected in areas of a thick crust and moderate melt supply. This can be the case for relatively robust magmatic segments as for instance the Atlantis massif OCC (Blackman et al., 2006, 2011; Drouin et al., 2009, 2010; Godard et al., 2009; Ildfonse et al., 2007) or the crustal transect exposed at the Adam Dome of the Kane megamullion (Dick et al., 2008, Figure 12d).

5.2. Emplacement and Crystal-Plastic Deformation of the NCC Gabbros

Clinopyroxene in the 16°30'N gabbros is characterized by different combinations of $\text{Mg}\#$ and TiO_2 contents (Figure 8). In particular, they show two distinct chemical trends in troctolites (Trend 1) and

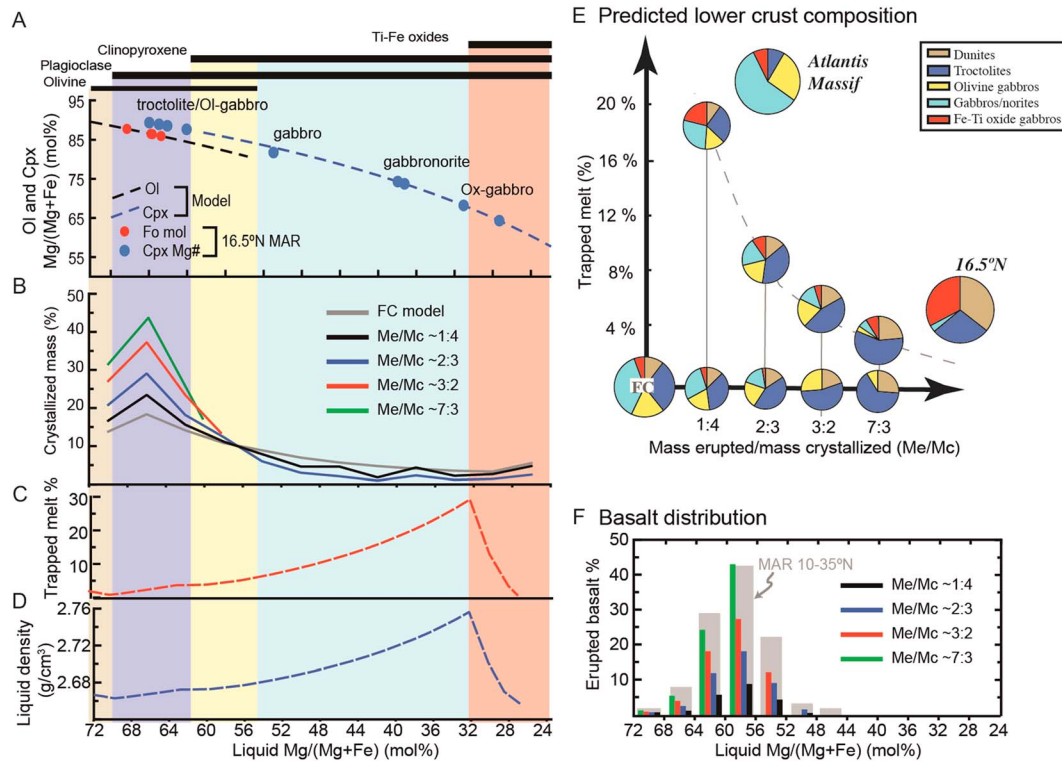


Figure 13. Liquid Mg/(Mg + Fe) (mol %) compositions versus (a) olivine Fo (black line and red circles) and clinopyroxene Mg/(Mg + Fe) (blue line and blue circles); (b) mass of gabbros (%) crystallized at each step of the thermodynamic model at different mass erupted /mass crystallized ratios (M_e/M_c); (c) trapped melt (%) and (d) liquid density calculated at each step of the crystallization process. (e) Compositional variability of gabbros resulted from the thermodynamic model. The origin represents the mass of gabbros neglecting eruption, on the x axis are depicted model outcomes for different M_e/M_c ratios if melt entrapment is ignored. The effect of melt entrapment is shown in the pie diagrams displayed vertically. The vertical displacement of each diagram depends on the total amount of trapped melt, as represented on the y axis. The gray dashed line connects model results for different trapped melt compositions (see text for details). The compositional variability of the gabbros dredged at the MAR 16.5°N region, and those from the Hole U1309 at the Atlantis massif (Blackman et al., 2011) are also reported. (f) Compositional variability of the basalts erupted at different M_e/M_c ratios compared to the basalts from the MAR 10–35°N segment.

gabbros/gabbronorites/oxide gabbros (Trend 2). The clinopyroxenes following Trend 1 show a sharp increase in TiO_2 at nearly constant Mg#, whereas those following Trend 2 display a gradual increase in TiO_2 at decreasing Mg# followed by (from Mg# ~70) a renewed decrease in TiO_2 . These chemical trends are typical for clinopyroxene from abyssal gabbros (see Coogan, 2007) and respectively explained as (Trend 1) evidence for magmatic metasomatism (i.e., melt-rock reactions) in a troctolitic matrix (see also Drouin et al., 2009; Lissenberg & Dick, 2008; Lissenberg & MacLeod, 2016; Sanfilippo & Tribuzio, 2013; Sanfilippo et al., 2013; Sanfilippo, Morishita, et al., 2015; Sanfilippo, Tribuzio, et al., 2015; Suhr et al., 2008, Trend 2) evidence for progressive magmatic differentiation followed by saturation in Fe-Ti oxides to form the oxide gabbros. The gradual decrease in clinopyroxene Mg# versus plagioclase An contents, and the variability of the Cpx suggest that the troctolite/gabbro/oxide-gabbro series crystallized from cogenetic melts evolving through fractionation of Ol, Pl, Cpx, and, finally, Ti-Fe oxides. Despite this, it seems obvious that the crystallization of Cpx in the troctolites also involved interactions between the olivine and plagioclase matrix and an evolved interstitial melts. This is consistent with the occurrence of large brown amphibole occurring as interstitial to oikocrystic grains within the troctolites (Figures 4c and 4d). This amphibole locally shows poikilitic textures with inclusions of irregular plagioclase chadacryst and small Ti-Fe oxides and is characterized by high TiO_2 , (K + Na) and Al, and negligible Cl contents (Figure 10). The poikilitic texture and the chemical compositions are reconcilable with a magmatic origin, indicating the crystallization of late-stage melts enriched in water and incompatible elements (see also Borghini & Rampone, 2007; Coogan et al., 2001; Tribuzio et al., 2000). Hence, in agreement with the extensive literature data for abyssal gabbros (e.g., Drouin et al., 2009; Lissenberg & Dick, 2008; Lissenberg & MacLeod, 2016; Rampone et al., 2016; Sanfilippo et al., 2013; Sanfilippo, Morishita, et al., 2015; Suhr et al., 2008), the enrichments in TiO_2 in the high-Mg# clinopyroxene

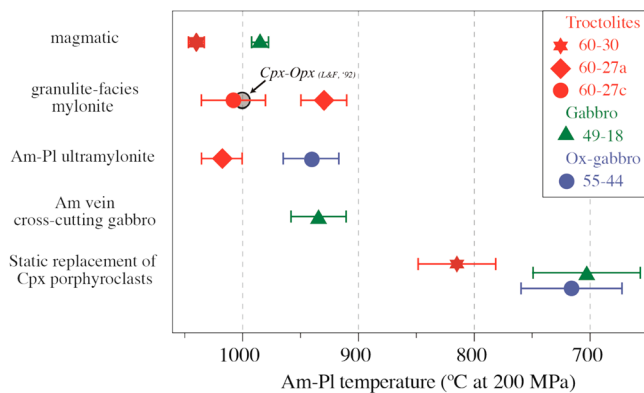


Figure 14. Temperature estimates calculated using the edenite-richterite amphibole-plagioclase thermometer (Holland & Blundy, 1994) assuming a pressure of 200 MPa. Mean values and standard deviations are given for individual textural amphibole-plagioclase types for each sample.

and the occurrence of magmatic amphibole with poikilitic texture testify that the 16.5°N troctolites underwent a process of magmatic metasomatism by an interstitial, evolved melt. Below, we show that evolved melts were also locally present at the onset of the deformation related to the detachment faulting.

A large proportion of the 16.5°N gabbros show textures associated with a process of deformation under high-temperature conditions (Figure 3). In particular, most samples have olivine, plagioclase, and clinopyroxene recrystallized in polygonal aggregates that are often associated with brown amphibole and Ti-Fe oxides. The amphibole neoblasts in all deformed troctolites (sheared, mylonites, and ultramylonites) are compositionally identical to the magmatic amphibole in the undeformed samples. In addition, the occurrence of deformed amphibole porphyroclasts in a sheared troctolite and the textural equilibrium with the other neoblastic phases (olivine, plagioclase, and clinopyroxene) clearly indicate that the formation of pargasitic amphibole in this sample predated the *anhydrous* granulite-facies deformation event.

The edenite-richterite amphibole-plagioclase thermometer of Holland and Blundy (1994) on adjacent grains of amphibole and plagioclase was selected to infer the temperature of recrystallization (Figure 14). In one mylonitic troctolite, the amphibole-plagioclase thermometry was also confirmed by two-pyroxene thermometry (Lindsley & Frost, 1992), which yielded similar temperature estimates (see Figure 14). Independent of rock-type, the amphibole-plagioclase thermometer provided high-temperature estimates for the granulite-grade deformation, varying between 930 °C and ~1010 °C. These estimates fall in the range of temperature estimated by Mehl and Hirth (2008), who showed that granulite-facies deformation in gabbros from Hole 735B occurred at temperatures as high as 946 ± 70 °C. These data suggest that the crystal-plastic deformation, which caused dynamic recrystallization and formation of neoblasts of olivine + clinopyroxene ± brown amphibole in the troctolites took place at hypersolidus conditions (close to the solidus temperature of the magmatic system). The high equilibration temperatures (1004 ± 20 °C; Figure 14) estimated on the basis of the coexistence of clinopyroxene-orthopyroxene in one troctolite mylonite confirm this hypothesis. We must note that these temperatures are very close to the stability limit of pargasitic amphibole at low pressures, which is considered to be at temperatures <1000 °C (Koepke et al., 2004, 2005, 2007). Hence, one possibility is that the temperature estimates for the mylonites give the crystallization temperature of an amphibole formed by a melt present during the deformation process. The chemical modifications in the neoblastic plagioclase of the sheared troctolite in Figure 7a, which has lower anorthite compared to that of the porphyroclasts (An_{78} and An_{81} , respectively), may also suggests that the granulite facies deformation in the mylonites might have occurred in the presence of interstitial melt.

Although this idea would need to be better constrained by a more thorough chemical characterization of the porphyroclastic and neoblastic minerals in the mylonites, the occurrence of melts at the onset granulite-grade deformation is consistent with the composition of the two ultramylonites shown in Figure 6. Both cases show a clear variation in the neoblastic assemblage crystallized during the strain localization from the protomylonite to the ultramylonite zone. In particular, although they are hosted in mineralogically different mylonites, both ultramylonites are formed by anorthitic plagioclase (An_{65} to An_{82}), Ti-rich pargasitic amphibole (TiO_2 1.7–3.7 wt %), and minor clinopyroxene (Mg# 75 to 85). In contrast to the host rocks (oxide gabbro and troctolite), they do not contain olivine, spinel, or Ti-Fe oxides (Figures 6 and 7). Felsic rocks containing plagioclase and amphibole are often found in abyssal and ophiolitic gabbros as crosscutting veins or discrete bodies associated with oxide-rich gabbros (Dick et al., 2000; Koepke et al., 2007, 2004; MacLeod et al., 2017; Tribuzio et al., 2014). These rocks are interpreted as the product of crystallization of silica-rich melts produced by extreme fractional crystallization of MOR-type basalt and/or partial melting of hydrothermally altered gabbro (see discussion in Tribuzio et al., 2014). Hence, one can argue that the ultramylonites represent the recrystallization of felsic material originally located within the host rock and mylonitized during the deformation event. However, this is at odds with the high anorthite in plagioclase (An_{83} – An_{65}) and Mg# in clinopyroxene and amphibole (Mg# 75–85 and 67–80, respectively) in the ultramylonites. In addition, the composition of the amphibole in the ultramylonite formed from a troctolite progenitor is similar to that of the amphibole in the

host rock (Figure 10b). The temperature estimates for the amphibole–plagioclase couples in the ultramylonite furnish very high values ranging from 930 °C to ~1020 °C, comparable to those in the host mylonites (Figure 14). Based on these data, it is plausible that the ultramylonite layers may represent melt-rich zones developed during the same deformation event as the host granulite-facies mylonites. The peculiar mineralogical and chemical compositions of these layers indicate that the melt had a hybrid composition, that is, high Mg/Fe and Ca/Na ratios, but rich in silica, incompatible elements, and water. The ultramylonite, hosted in an oxide-gabbro, has plagioclase showing a strong increase in anorthite component (~82 mol %) compared to that in the host mylonite (~46 mol %). The high anorthite is also ascribable to the occurrence of a water-bearing melt during the crystallization of the neoblastic plagioclase (Berndt et al., 2005). Further investigation will shed light on the nature of this hybrid melt and the mechanism that allowed the strain localization to form the ultramylonite.

In summary, our data suggest that the granulite-facies deformation event recorded by the gabbros occurred shortly after the crystallization of the magmatic phases. This event may have possibly enhanced the expulsion of the liquid from the crystal framework, allowing the formation of oxide-rich seams within the gabbros and/or discrete oxide-rich horizons often associated with high-temperature deformation. A similar process has been proposed by Natland and Dick (2001) to explain the close association of oxide-rich layers and granulite-grade mylonites in gabbros from Hole 735B at Atlantis Bank. We note though that thermometry estimates of the mylonites analyzed by Miranda and John (2010) from Hole 735B yielded temperatures <910 °C generally lower than those reported in the present study. Nonetheless, the occurrence of high-temperature ultramylonites likely formed in the presence of melt suggests a complex interplay between deformation and melt percolation that has also been proposed for mylonitic rocks drilled at the inside-corner high of the MAR at 23°N (Agar & Lloyd, 1997).

5.3. Hydrothermal Alteration

Distinctive black hornblende-rich veins locally crosscut the gabbros at high angle to the high-temperature metamorphic foliation of the host rock. These vein-filled fractures represent formation during brittle deformation that is also related to the crystallization of hornblende pseudomorphs after the magmatic clinopyroxene in the host rock, indicating the host gabbros enjoyed migration of hydrous fluids from the vein into the gabbro. This process also accounts for the formation of secondary plagioclase (albitic in composition) crystallizing within microcracks connecting the different amphibole pseudomorphs.

Both the vein and clinopyroxene pseudomorph hornblende in the gabbros have appreciable Cl contents (0.1–0.2 wt %) similar to that in hydrothermal amphiboles in other abyssal gabbros (Coogan et al., 2001; Tribuzio et al., 2014). This suggests that both amphibole types formed by interaction with water-rich fluids likely derived from seawater (see also Alt & Bach, 2006). However, the amphibole from the veins has lower Mg# (70–77) and higher TiO₂ contents (3.0–3.3 wt %) compared to the coronitic hornblende adjacent to the veins in the gabbro (Mg# = 75–81; TiO₂ < 1.5 wt %), approaching the Ti and Al of the magmatic pargasite in the troctolites (Figure 10). The chemical map in Figure 7d shows that the hornblende statically replacing the pyroxene is associated with fine-grained plagioclase having very low anorthite contents (20–25 mol %) and is typically found in microcracks. Temperature estimates based on plagioclase–amphibole pairs yield amphibolite facies temperatures of ~700 °C (Figure 14). This suggests that the hornblende replacing the clinopyroxene likely formed by interaction of the magmatic phases with seawater-derived fluids (Coogan et al., 2001), which caused the recrystallization of Na-rich plagioclase within cracks and microveins (see also Tribuzio et al., 2014). On the other hand, the high Ti and Al in the hornblende from the veins suggest that magmatic components were likely still present within the fluids forming these veins. This is in agreement with the high temperature (920–970 °C) indicated by the plagioclase–amphibole thermometers on a euhedral plagioclase contained in the vein. The occurrence of magmatic components in the hornblende-rich veins was also inferred for the amphibole-rich veins cross-cutting gabbro at Atlantis Bank (Alt & Bach, 2006) and in the Ligurian ophiolites (Tribuzio et al., 2014) and related to fluids exsolved from highly evolved melts residual from the magmatic differentiation process.

In summary, the microtextures and the chemical variability of the amphibole forming the hydrothermal hornblende offer a snapshot to the retrograde evolution of this portion of the lower crust exhumed by a detachment fault. In line with previous studies on abyssal and ophiolitic gabbros, we propose that a magmatic component was still present during the first stages of hydrothermal alteration at the ductile–brittle

transition. This stage was followed by further cooling, by the ingress of seawater along cracks, and by the static replacement of the magmatic phases by green hornblende and albitic plagioclase.

6. Conclusions

The lower oceanic crust exposed in the 16.5°N region of the MAR formed in a detachment fault system characterized by a moderate to low magma supply. Dredge hauls indicate a bimodal composition of the lower crust that is formed by a high proportion of dunites and troctolites associated with evolved gabbro-norites and oxide gabbros, and a lack of intermediate rock types. Using a thermodynamic model, we infer that a similar bimodal distribution of the lower oceanic crust is expected in regions where gabbroic intrusions are scattered within partly serpentinized mantle peridotite. The formation of these *ephemeral* magma chambers within the mantle lithosphere causes a high eruption rate, which in turn allows most of the melt to be erupted after moderate degrees of fractionation. This idea is also consistent with the evidence that small amounts of melt were present at the onset of the high-temperature deformation related to the oceanic detachment. The development of porphyroclastic to mylonitic fabrics occurred at near-solidus conditions (~1000 °C) and was likely associated with the expulsion of interstitial, evolved melts from the crystal matrix. This mechanism enhanced the formation of disconnected oxide-gabbro seams or layers often associated with crystal-plastic fabrics in the host gabbros. The high-temperature deformation was followed by hydrothermal alteration marked by the formation of amphibole-rich veins at high-temperature conditions (~900 °C). This study suggests that the compositional variability of the lower oceanic crust formed at the 16.5°N region of the MAR is the consequence of the complex interplay between low melt supply and high-temperature deformation representing the deep expression of the detachment fault.

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